

AD-A232 446

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE January 14, 1991		3. REPORT TYPE AND DATES COVERED Final Report (July 1, 1986-Dec. 31, 1990)
4. TITLE AND SUBTITLE Fundamental Research on Tribology			5. FUNDING NUMBERS DAAL03-86-F-0076	
AUTHOR(S) James L. Lauer			PERFORMING ORGANIZATION REPORT NUMBER MAR 15 1991 G D	
PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of Mechanical Engineering, Aeronautical Engineering & Mechanics Rensselaer Polytechnic Institute Troy, NY 12180-3590			10. SPONSORING/MONITORING AGENCY REPORT NUMBER ARO 235-2541-EG	
SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P. O. Box 12211 Research Triangle Park, NC 27709-2211				
11. SUPPLEMENTARY NOTES The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A multidisciplinary program of basic research was conducted with emphasis on potential ways of reducing friction and wear under conditions of boundary lubrication. A special aim was the development of lubricating systems for applications at temperatures above 300°C. Both experimental and theoretical (computer modeling) approaches were used in parallel. Among the most important results were: <ul style="list-style-type: none"> • Stable carbonaceous gases or vapors (ethylene, benzene propane, propanol) form a lubricating carbon deposit on nickel-containing steels at temperatures above 350°C. Under wear fresh metal surfaces are exposed providing continuous catalytic regeneration of the solid lubricant as long as the gas is supplied. • The same concept also works on ceramic surfaces such as silicon nitride, Sialon, silicon carbide or zirconia. However, the nature of the carbon (possibly cracking-type coke) is spectroscopically different. Friction coefficients as low as 0.02 and negligible wear could be achieved. • A parallel ultrahigh vacuum SEM study showed catalytic carbon deposition on nickel from ethylene in the same temperature range where the friction coefficient was low. • New computer models of polymer friction in the temperature-controlled region and of EHD by fracture mechanics were devised. 				
14. SUBJECT TERMS Friction, wear, tribology, carbon, polymers, nickel, steel, ceramics, high temperature lubrication			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

GENERAL INSTRUCTIONS FOR COMPLETING SF 298

The Report Documentation Page (RDP) is used in announcing and cataloging reports. It is important that this information be consistent with the rest of the report, particularly the cover and title page. Instructions for filling in each block of the form follow. It is important to *stay within the lines* to meet optical scanning requirements.

Block 1. Agency Use Only (Leave blank).

Block 2. Report Date. Full publication date including day, month, and year, if available (e.g. 1 Jan 88). Must cite at least the year.

Block 3. Type of Report and Dates Covered. State whether report is interim, final, etc. If applicable, enter inclusive report dates (e.g. 10 Jun 87 - 30 Jun 88).

Block 4. Title and Subtitle. A title is taken from the part of the report that provides the most meaningful and complete information. When a report is prepared in more than one volume, repeat the primary title, add volume number, and include subtitle for the specific volume. On classified documents enter the title classification in parentheses.

Block 5. Funding Numbers. To include contract and grant numbers; may include program element number(s), project number(s), task number(s), and work unit number(s). Use the following labels:

C - Contract	PR - Project
G - Grant	TA - Task
PE - Program Element	WU - Work Unit Accession No.

Block 6. Author(s). Name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. If editor or compiler, this should follow the name(s).

Block 7. Performing Organization Name(s) and Address(es). Self-explanatory.

Block 8. Performing Organization Report Number. Enter the unique alphanumeric report number(s) assigned by the organization performing the report.

Block 9. Sponsoring/Monitoring Agency Name(s) and Address(es). Self-explanatory.

Block 10. Sponsoring/Monitoring Agency Report Number. (If known)

Block 11. Supplementary Notes. Enter information not included elsewhere such as: Prepared in cooperation with...; Trans. of...; To be published in.... When a report is revised, include a statement whether the new report supersedes or supplements the older report.

Block 12a. Distribution/Availability Statement. Denotes public availability or limitations. Cite any availability to the public. Enter additional limitations or special markings in all capitals (e.g. NOFORN, REL, ITAR).

DOD - See DoDD 5230.24, "Distribution Statements on Technical Documents."

DOE - See authorities.

NASA - See Handbook NHB 2200.2.

NTIS - Leave blank.

Block 12b. Distribution Code.

DOD - Leave blank.

DOE - Enter DOE distribution categories from the Standard Distribution for Unclassified Scientific and Technical Reports.

NASA - Leave blank.

NTIS - Leave blank.

Block 13. Abstract. Include a brief (*Maximum 200 words*) factual summary of the most significant information contained in the report.

Block 14. Subject Terms. Keywords or phrases identifying major subjects in the report.

Block 15. Number of Pages. Enter the total number of pages.

Block 16. Price Code. Enter appropriate price code (*NTIS only*).

Blocks 17. - 19. Security Classifications. Self-explanatory. Enter U.S. Security Classification in accordance with U.S. Security Regulations (i.e., UNCLASSIFIED). If form contains classified information, stamp classification on the top and bottom of the page.

Block 20. Limitation of Abstract. This block must be completed to assign a limitation to the abstract. Enter either UL (unlimited) or SAR (same as report). An entry in this block is necessary if the abstract is to be limited. If blank, the abstract is assumed to be unlimited.

1. STATEMENT OF PROBLEMS STUDIED

The purpose of this multifaceted program of interdisciplinary basic research was to find ways of reducing friction and wear under conditions of boundary lubrication. Special emphasis was to be given to lubrication at temperatures of 300°C and above, and at high loads, which requires special additives to liquid lubricants, replenishable solid lubricants, or tribosurfaces of materials requiring no lubricants. Both experimental and theoretical (computer modeling) approaches were to be used in parallel.

1.1. Approach and Comments

Surface science, mechanical engineering, chemistry and chemical and materials engineering, and computer science were among the disciplines used. Faculty and graduate students from the Departments of Mechanical Engineering, Chemical Engineering and Materials Engineering participated.

The program experienced severe funding cuts every year during its four-year lifetime. Therefore only those areas of research were continued in successive years, that appeared to be the most promising. The last (ninth) half-year was a no-cost extension with only the P.I. working on the project.

The research yielded 39 publications in archival journals or books. One paper won a Best Paper Award (Paper #3 on the List of Publications). Every participating professor was *invited* by a national engineering or scientific society at least once during the life of the project to speak on work sponsored by this contact.

2. SUMMARY OF THE MOST IMPORTANT RESULTS

2.1 Lubricating Carbon Films on Nickel and Palladium

2.1.1 Concept

The formation of carbon ("coke") on transition metal surfaces during the catalytic dehydrogenation of the hydrocarbons has been well-known in petroleum refining for a long time. If the carbon is also lubricating--as was found to be the case in this research program--than it could be exploited for high-temperature lubrication with continuous feed. The concept is this:

- Feed a thermally stable gas from a supply at ambient temperature to hot (350-650°C) friction surfaces.
- Catalytically decompose this gas at the friction surfaces to form a lubricating carbon deposit. Water (steam) is the only other product.
- Preferred metallic surfaces are alloys containing nickel and palladium because of their known catalytic activity.

2.1.2 Approach

Fig. 1 shows the pin-on-disc apparatus used. Its core is the inner shell, a prolate ellipsoid of revolution containing the friction contact at one focus and a quartz halogen lamp, the heater, at the other. Treatment gases (ethylene) are injected only into the conjunction region. The surrounding environment can be air or an inert gas. The outer chamber is filled with an inert gas; it provides a safety shield. Friction is measured continuously, wear periodically by determining

wear track volume and pin volume change. Contact pressures ranged between 200 and 800 MPa, linear velocities between 3 and 30 cm/sec.

Fig. 2 shows friction vs. time traces obtained at different temperatures with a sapphire pin on a silicon nitride disc overcoated with nickel. Note the sharp drop of friction on ethylene introduction especially at 500°C. The change is more sluggish at the other temperatures. Wear changes paralleled the friction changes.

Fig. 3 gives the steady state surface carbon coverage, as determined by Auger electron spectroscopy (AES) at various substrate temperatures. This experiment was carried out independently on a pure Ni(110) film in a different RPI laboratory. It is clear that this result is in good agreement with the temperature dependence of film formation in the wear experiment.

During the wear experiment fresh metal surfaces were continuously produced and graphitic carbon deposits formed. These deposits adhered strongly to the substrate, being partly dissolved in it.

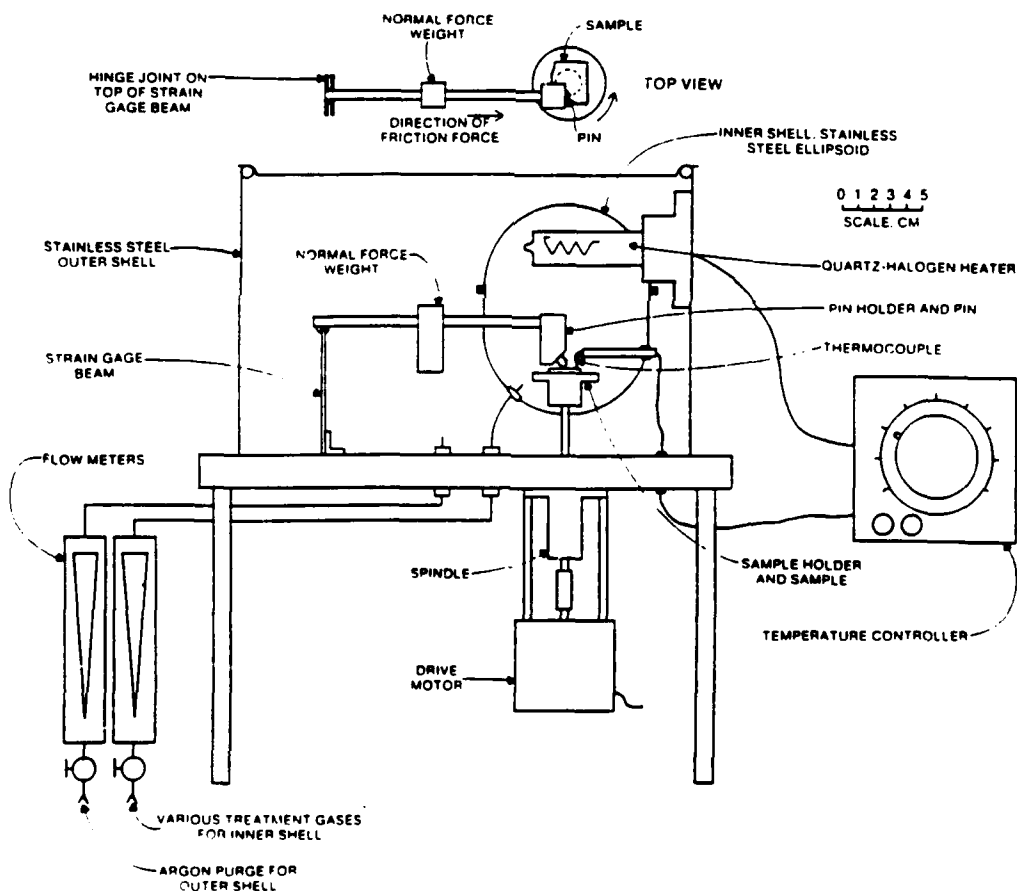


Fig. 1 Pin-on-Disc Apparatus

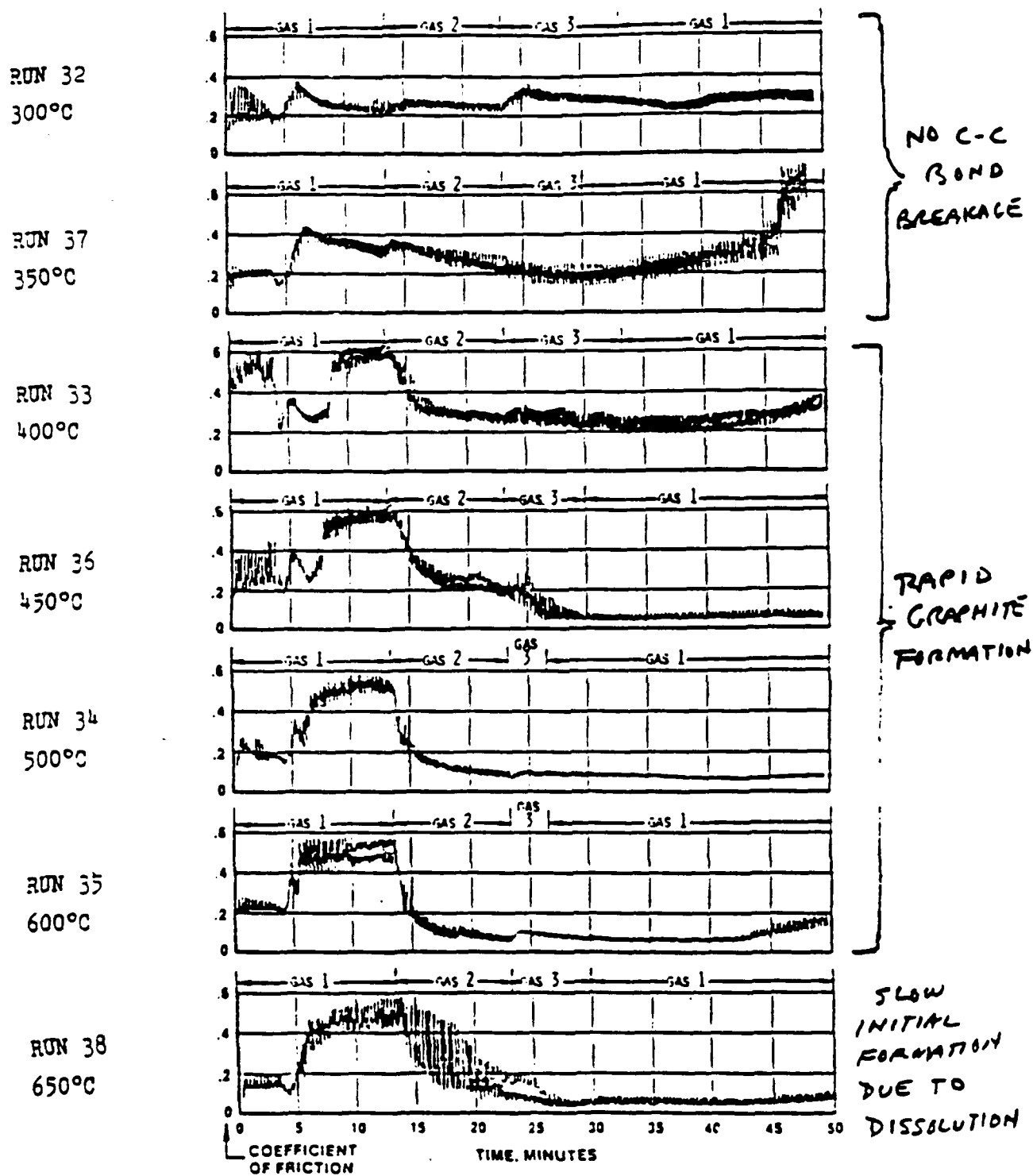


Fig. 2 Changes of Friction Coefficient with Temperatures in the Pin-on-Disc Tribometer. (Nickel-coated Sialon disc, sapphire pin. Gas 1 = He+Ar, Gas 2 = C₂H₄ + Ar, Gas 3 = C₂H₄ + H₂+Ar)

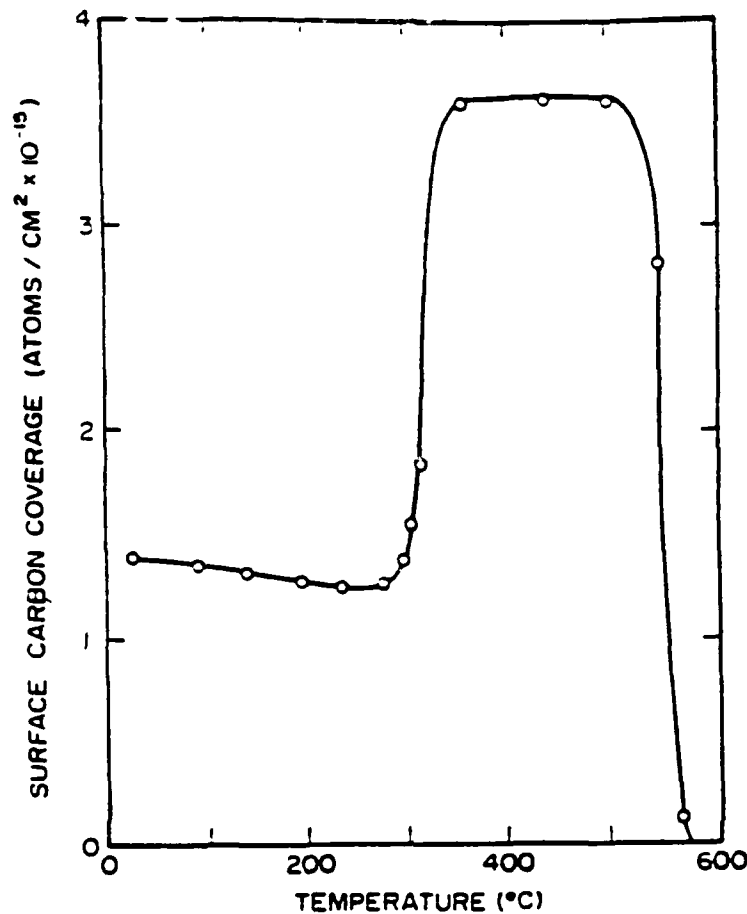


Fig. 3 Steady state surface carbon coverage, as determined by AES, at various substrate temperatures.

2.2 Lubricating Carbon Films on Silicon Nitride (Sialon) and Nitride (Sialon) and Silicon Carbide

A major breakthrough in this study was the finding that lubricating carbon was produced on Sialon and other plates in the above-mentioned experiment even in the absence of a nickel overcoat. Friction coefficients as low as 0.02 could be achieved for loads similar to those used in the nickel experiments. The drop of friction on introduction of ethylene was two step; a wear-in period and a final period (Fig. 4). Raman spectra obtained from the carbon coating, which was formed only on the wear track, showed significant differences between the carbon now produced and the (presumably) graphite produced on nickel. Furthermore the Raman spectra also indicated that a silicon carbide (SiC) was produced in the wear-in step. SiC could provide nuclei for further carbon deposition. Raman spectroscopy proved to be an invaluable tool in the characterization of the lubricating carbon.

• TRIBOCHEMICAL WEAR-IN

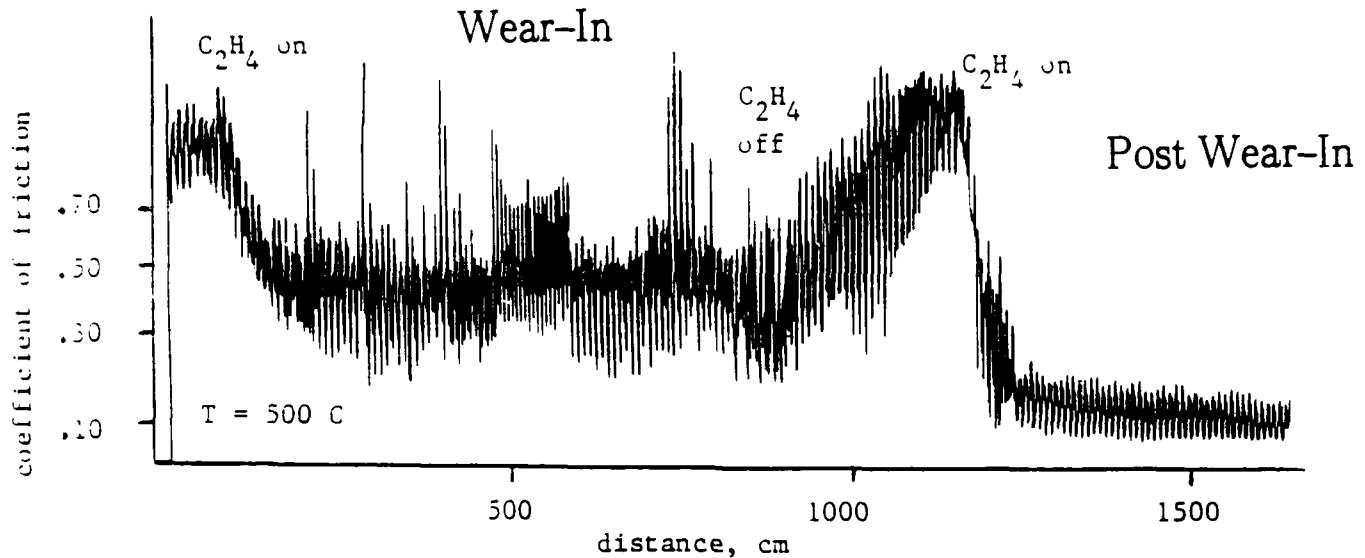


Fig. 4 Coefficient of friction vs. sliding distance for sapphire on bare Sialon. The ethylene reaction produces a much lower coefficient of friction after the wear-in period

This work is continuing under partial industrial sponsorship. The concept might be applicable to the uncooled diesel engine projected, inter alia, by an Army group.

2.3 Influence of Friction Heating on the Sliding Friction of Elastomers and Polymers

Both theoretical and experimental research led the thermal control model, which is based on the concept that surface temperatures in a sliding contact cannot increase indefinitely as conditions are made more severe. Eventually an upper-bound, limiting temperature T_f is attained. This is called the Friction Defined Temperature, which remains at a constant value as the severity of the sliding is increased.

Only an extremely thin layer of material at the surface need be at T_f . Once thermal control has been initiated, the friction coefficient is given by

$$\mu = \frac{1.45(T_f - T_a)}{KP} \left(\frac{k\rho c}{VB} \right)^{1/2}$$

where

T_a	ambient temperature
K	proportion of generated heat to moving surface
P	interface pressure
k	thermal conductivity
ρ	density
c	specific heat
V	sliding speed
B	length of contact in direction of sliding

The effect of thermal control for three different loads, $W_1 < W_2 < W_3$ is shown in Fig. 5. The decrease of friction coefficient with increasing speed is characteristic of this operation. This result can be especially important to the friction of tires on pavement: The braking distance at high speeds is increased further by a lower coefficient of friction.

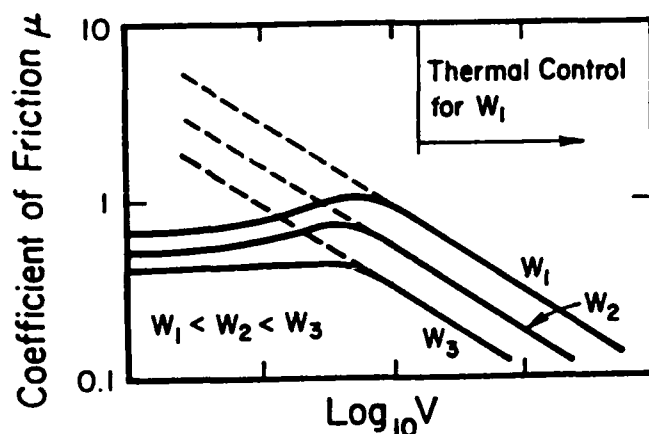


Fig. 5 The effect of thermal control on the level of friction.

2.4 Sliding Experiments in the Scanning Electron Microscope (SEM)

An SEM was modified to allow the direct IN SITU observation of friction and wear on a microscopic scale. A pin was made to plow into the mantle of a rotating cylinder. The process was recorded on videotape. The nature of the wear debris was shown to depend on the absence or presence of a lubricant. Plastic deformation can play an important part in wear. A plastically deformed layer can cover grooves and scratches of the original surface and thereby reduce their function as lubricant reservoirs. Plastically extruded layers were observed on either side of plowing marks when wear became severe. These layers became a source of wear debris in the form of platelets.

The videotapes documenting this work, which encompassed different materials and experimental parameters, have been very popular at lectures and seminars on wear. The modified SEM head is now commercially available.

2.5 Fractal Geometry Applied to Tribology

Fractal geometry is clearly a natural model for describing such self-similar phenomena as elastohydrodynamic lubrication (EHD) and micro-EHD. In other words there are asperities on asperities and all them can be elastically deformed. A new exponential scaling law was discovered, making it possible to join continuum mechanics to surface physics or chemistry.

2.6 Facilitation of Metal Forming and Shaping by Sulfur Compounds

When such compounds as disulfides, sulfides or thiophene were present as vapors in the environmental air in a steel pin-on-disc fixture designed to simulate a cutting operation, friction could be greatly reduced. This finding was not new; however, the location of the sulfur on the steel disc was surprising. It was found by Auger electron spectroscopy (AES) only in the wear

track or the wear debris and than that of only some 40 nm below the surface. The top layer was an iron oxide of different crystal shape than a normal oxide would be. Later it was learnt that a group at Case Institute of Technology found the same effect when iron was first exposed to sulfurous vapors and subsequently heated in air at 700°C.

The implication of this finding is that the material reducing friction could be an iron oxide produced by iron sulfide conversion rather than iron sulfide. If this concept can be further extended, numerous applications are likely.

2.7 Steady-State Moving Loads on Elastic-Plastic Solids

Local stress and deformation fields for contact loads moving steadily on an elastic-plastic, strain-hardening solid under plane strain and small-scale yielding conditions were analyzed numerically on a Super-Computer by a steady-state finite element iterative procedure. The numerical results revealed the development of elastic unloading zones trailing the moving contact load. The influence of strain hardening and friction condition on the local stress and deformation states became apparent.

2.8 Other Results

As is clear from the titles of the 39 publications on work partially funded by this project, many other research results were obtained. Much of the work seeded by this contract is continuing.

LIST OF PUBLICATIONS

1. "Friction Polymers," J.L. Lauer and W.R. Jones, Jr., Preprint for the 1986 Tribology Conference, Pittsburgh, PA, October 1986. Published in ASLE Special Publication No. 21 of Magnetic Recording Media, pp. 14-23 (1986).
2. "Heat Generation and Friction in Rotating Bands," C.M. McC Ettles, ASLE Transactions, Vol. 29, No. 3, pp. 312-320, (1986).
3. "Parameters Affecting the Kinetic Friction of Ice," Akkok, M., C.M. McC Ettles and S.J. Calabrese, ASME J. of Tribology, 109(3), 552-561 (July 1987).
4. "Modification of SEM for In-Situ Liquid-Lubricated Sliding Studies," W.W. Holzhauer, and S.J. Calabrese, ASME/ASLE Tribology Conference, Pittsburgh, PA., ASLE Transactions, 30 3(1987).
5. "Asymptotic Analyses in Isothermal Fluid Film Lubrication Theories," F.F. Ling, Society for Industrial and Applied Mathematics, Vol. 28, No. 3, pp. 343-366 (1986).
6. "Optical and Other Properties Changes of M-50 Bearing Steel Surfaces for Different Lubricants and Additives Prior to Scuffing," J.L. Lauer, N. Marxer, and William R. Jones, Jr., ASLE Transactions, 29(4), 457-466 (1986).
7. "The Lubrication of Metals and Ceramics by the Catalytic Formation of Carbon Films," J.L. Lauer and Bruce Bunting. Proceedings of the Society of Automotive Engineers, Paper No. 870022, SAE SP700, Adiabatic Engines and Systems, 41-48 (1987).
8. "Surface Shear Near the Contact Line of a Binary Evaporating Curved Thin Film," C.J. Parks and P.C. Wayner, Jr., American Institute of Chemical Engineers Journal, 33 1-10 (1987).
9. "Lubricants and Lubricant Additives Under Shear Studied Under Operating Conditions by Optical and Infrared Spectroscopic Methods," J.L. Lauer and Y-J. Ahn, STLE Transactions, 31 1, pp. 120-127 (1988).
10. "Infrared Emission FTIR Applied to Frictionally Transferred PTFE and to Frictionally Stressed Ceramic Surfaces," J.L. Lauer and W.R. Jones, Jr., Abstract, Proceedings of the Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy, March 1987, page 1010.
11. "Modification of SEM for IN-SITU, Liquid-Lubricated Sliding Studies," W. Holzhauer, and S.J. Calabrese, ASLE Transactions, 30 3(1987).
12. "Scaling Law for Contoured Length of Engineering Surfaces," F.F. Ling, J. Appl. Phys. 62(6), 2570-2572 (September 1987).
13. "On Fractal Dimension of Engineering Surfaces," Section 4.20 in Approaches to Modeling of Friction and Wear, F.F. Ling, (F.F. Ling and C.H.T. Pan, eds.) Springer Verlag, New York, Inc. 1987, 170 pp.
14. "A Model for the Transport Phenomena Associated with a Two-Component Meniscus Evaporating into a Multicomponent Vapor," C.J. Parks and P.C. Wayner, Jr., AICHE Symposium Series 257, 83, 122-127, 1987.

15. "Parameters Affecting the Kinetic Friction of Ice," M. Akkok, C.M.McC. Ettles, and S.J. Calabrese, ASME J. of Tribology, 109(3), 552-561 (July 1987).
16. "Three-Dimensional Computation of Thrust Bearings," C.M.McC.Ettles, Proc. 13th Leeds-Lyon Symposium on Tribology, Fluid Film Lubrication-Osborne Reynolds Centenary, Elsevier, pp. 95-104 (Nov. 1987).
17. "The Analysis of a Self-Acting Flexible Foil Slider Bearing," C.E. Hardie and C.M.McC. Ettles, ASME Paper 87-Trib-42, ASME J. of Tribology, Vol. 110, pp. 678-684 (Oct. 1988).
18. "The Influence of Frictional Heating on the Sliding Friction of Elastomers and Polymers," Rubber Chemistry and Technology, 61, 119-137 (April 1988).
19. "The Influence of Desorption Kinetics on Hydrogen Permeation in Iron," Applied Surface Science, 29, 1-19 (1987).
20. "Investigation of Friction Transfer Films of PTFE by Infrared Emission Spectroscopy and Phase-Locked Ellipsometry," J.L. Lauer, Bruce Bunting and W.R. Jones, Jr., Tribology Transactions, 31, 2, 282-288 (1988).
21. "Catalytic Generation of Lubricants from Carbonaceous Gases on Surfaces Undergoing Friction at High Temperatures," J.L. Lauer and B.G. Bunting, SAE Special Publication SP 738, "Recent Developments in the Adiabatic Engine," ISSN 0148-7191, pp. 51-59 (1988).
22. "High Temperature Solid Lubrication by Catalytically Generated Carbon," J.L. Lauer and B.G. Bunting, Tribology Transactions, 31(3), 338-349 (1988).
23. "Lubrication by a Smectic Liquid Crystal," T.E. Fischer, S. Bhattacharya, R. Salher, J.L. Lauer and Y-J. Ahn, Tribology Transactions, 31(4), 442-448 (1988).
24. "Friction Polymer Buildup on Video Head by Ellipsometry and Infrared Emission," J.L. Lauer, Invited Lecture at the Symposium in Information Storage Technology, Sponsored by the American Chemical Society, Los Angeles, CA, September 25-30, 1988. Published in the Polymer Preprints, Division of Polymer Chemistry, American Chemical Society, Vol. 29, No. 2, 275-276 (1988).
25. "In-Situ SEM Study of Boundary Lubricated Contacts," W. Holzhauer and F.F. Ling, Tribology Transactions, 31(3), 359-368 (1988).
26. "The Reaction of Hydrogen with Oxygen on a Polycrystalline Iron Surface," M. Arbab and J.B. Hudson, J. Vac. Sci. Technol. A6, 775 (1988).
27. "The Kinetics and Mechanism of Oxygen Uptake on a Polycrystalline Iron Surface," M. Arbab and J.B. Hudson, Surface Science, 206, 317 (1988).
28. "Steel Hardness Effects in Boundary Lubricated Sliding: An In-Situ SEM Study," S. Calabrese and W. Holzhauer, STLE Preprints, No. 88-TC-2E-1, Baltimore, October 1988.
29. "The Titration of Oxygen on a Polycrystalline Iron Surface by Hydrogen Permeation," M. Arbab and J.B. Hudson, Surface Science 20, 183 (1989).

30. "Continuous High Temperature Lubrication of Ceramics by Carbon Generated Catalytically," J.L. Lauer and Scott R. Dwyer, Material Research Society Symposium Proceedings, Vol. 140, pp. 363-368 (June 1989).
31. "Regeneration of Solid Lubricants by Chemical Reaction on Tribological Surfaces," Proceedings of the 5th International Congress on Tribology, Vol. 1, pp. 168-171 (1989) [The Finnish Society for Tribology, VTT.KOT, Metallimiechenkuja 6, 02150 ESPOO, Finland, ISBN 952-90080-1-5].
32. "Analysis of NiO-Coated and Bare Ceramic Surfaces (Si_3N_4 and SiC) and of Lubricating Carbonaceous Layers Formed Thereon by Raman and Auger Electron Spectroscopies During Friction and Wear." J.L. Lauer and L. DuPlessis, Article No. 655. 41st Pittsburgh Conference and Exposition on Analytical Chemistry and Applied Spectroscopy. The Jacob K. Javits Convention Center, NY, March 1990.
33. "Formation of Adsorbed and Chemically Reacted Sulfur Films on Steel Surfaces during Sliding," J. L. Lauer, P.A. Benoy, B.L. Vlcek, and S.J. Calabrese. Tribology Transactions 33 (4), 586-594 (1990).
34. "Continuous High Temperature Lubrication of Ceramics by Carbon Generated Catalytically from Hydrocarbon Gases," J. L. Lauer and S.R. Dwyer. Tribology Transactions 33 (4), 529-534 (1990).
35. "Lubrication of Ceramics by Surface-Generated Carbon from Gaseous Feed," James L. Lauer and S.R. Dwyer. Proceedings of the Japan International Tribology Conference, Vol. II, pp. 989-994 (1990).
36. "Optical and Spectroscopic Studies of Carbon-Overcoated Hard Computer Discs," J.L. Lauer and Leon P. DuPlessis. Proceedings of the Japan International Tribology Conference, Vol. II, pp. 1297-1300 (1990).
37. "Tribochemical Lubrication of Ceramics by Carbonaceous Vapors," J.L. Lauer and S.R. Dwyer. STLE Preprints, No. 90-TC-5A-1.
38. "Relation between Deposition Parameters, Structure, and Raman Spectra of Carbon Overcoats on Magnetic Storage Discs," J.L. Lauer and L. DuPlessis, STLE, SP-29, 71-79 (1990).
39. "SEM Observations of the Sliding Behavior of Al_2O_3 and CBN against Steel," S.J. Calabrese and S.F. Murray, Scanning, Vol. II, pp. 231-236 (1989).

SCIENTIFIC PERSONNEL

Frederick F. Ling, William Howard Hart Professor of Mechanical Engineering
 James L. Lauer, Professor of Mechanical Engineering
 John B. Hudson, Professor of Materials Engineering
 Peter C. Wayner, Jr., Professor of Chemical Engineering
 Christopher M.M. McC. Ettles, Professor of Mechanical Engineering
 T.-L. (Sam) Sham, Associate Professor of Mechanical Engineering

Research Staff

S.F. Murray
S.J. Calabrese

Doctoral Candidates:

J.D. Cogdell - Completed graduation requirements and left in September 1987, Mechanical Engineering
J.G. Truong - Completed graduation requirements and left in September 1987, Chemical Engineering
W. Holzhauer - Completed graduation requirements and left in December 1987, Mechanical Engineering
B.G. Bunting - Completed graduation requirements and left in December 1987, Mechanical Engineering
C.J. Parks - Completed graduation requirements and left in December 1987, Chemical Engineering
Bin Han, Materials Engineering
N.K. Kang, Mechanical Engineering
M. Arbab, Materials Engineering, Completed graduation requirements and left in May 1989, Mechanical Engineering
Leon DuPlessis, Completed graduation requirements and left in August 1990, Mechanical Engineering
P. Benoy, Completed graduation requirements and left in May 1988, Mechanical Engineering

Accession For	
NTIS - CRA&I	<input checked="checked" type="checkbox"/>
ENR - TAB	<input type="checkbox"/>
Unpublished	<input type="checkbox"/>
Justification	
By	
Date	
Availability Codes	
Date	Avail and/or Special
A-1	

